Economic optimization and integrated river basin modelling

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Abstract

In order to reach the water quality objectives, as set by the EU Water Framework Directive, emission loads have to be reduced and pollution abatement plans set up for all river basins by 2008. With high environmental concerns and limited financial resources, good water quality has to be reached in the most cost effective way. This paper discusses the use of a linear programming model to optimize the cost and effectiveness of the abatement of nitrogen emissions for the Grote Nete river basin (Belgium). The following abatement measures are considered: waste water treatment, a subsidized reduction of pigs, and manure processing. It is found that a good water quality in the Grote Nete will involve an annual cost of at least €6 million until 2015.

Keywords: river basin management, decision-support, economic optimization, cost-effectiveness analysis, nitrogen, Belgium, Water Framework Directive.

1 Introduction

Given the numerous and increasing pressures on water resources, it is vital that effective legislative instruments help to secure existing resources for future generations. Since 2000, the European Union (EU) Water Framework Directive (2000/60/EC), further abbreviated as WFD, enforces the sustainable use of water throughout Europe. Its fundamental objective is to maintain a 'high status' of all waters, i.e. groundwater, surface water, transitional and coastal water. Any deterioration of the existing status must be prevented and by 2015 a 'good status' must be achieved for all European waters. River basin action plans, including the measures that need to be taken to achieve the goals of the WFD, have to be set up by the EU Member States by 2008.

Within the framework of these plans, emission based regulations and an approach based on environmental quality objectives have to be combined.

Consequently, a given pollution abatement measure is not to be considered as a goal in itself, but as a pragmatic action, established with the purpose of reaching an environmental objective. By combining different kinds of measures, the action plans should allow the creation of synergies and complementarities between different actions, such as legally binding measures, technical measures, financial tools, voluntary agreements and education.

Considering the nitrate pollution, the former Urban Waste Water Directive (91/271/EEC) – that e.g. imposes nutrient removal in waste water treatment plants in “sensitive” areas – and the Nitrate Directive (91/676/EEC) – dealing with the abatement of nitrate pollution of diffuse origin – will have to be implemented. However, taking into account that most rivers in Belgium suffer from a high nitrate load, it is expected that these traditional emission based measures will not be sufficient and that supplementary measures will be required to achieve the environmental quality objectives of the WFD.

Within the context of these additional measures, the cost and effectiveness of the abatement plans becomes important and should be optimized. Until now, however, data on costs and environmental effectiveness are sparse. Also, the comparison of the costs and the effectiveness of different alternatives is problematic. van der Woerd et al. [1] and Meynaerts et al. [2] elaborate on the use of cost-effectiveness for river basin management, respectively for the Netherlands and Belgium. Interwies et al. [3] furthermore developed a methodology for selecting the most cost-effective combination of measures and collected the available cost and effectiveness data for Germany. van der Veeren [4] finally did similar work and applied an economic analysis of nutrient abatement policies in the Rhine basin. In this paper, a methodology is elaborated to identify the least-costly set of measures that will achieve a required water quality level with respect to the nitrogen compounds.

2 Economic analysis for river basin management

As the size and complexity of watersheds increase, so does the exercise in finding a good implementation strategy (Srivastava et al. [5]). For example, one might identify a measure that greatly reduces the pollutant load, but the cost of implementation might also be excessive. The need therefore exists for an optimization algorithm that combines water quality and economic objective functions. Often used economic optimization criteria are cost-minimization and profit-maximization. For cost-minimization, measures have to be combined such that objectives can be achieved at least cost (cost-effectiveness analyses). For profit-maximization, the loss of welfare for those who have to pay for the measures is minimized (cost-benefit analyses). More extensive economic modelling, such as general equilibrium models, which seek to explain production, consumption and prices at macro scale, are not discussed here.

2.1 Cost-effectiveness analysis

When the levels for pollution load reduction are set externally, e.g. as environmental standards, cost-effectiveness analysis can be applied to find out how the environmental standards can be achieved at least cost (McAllister [6], van der Veeren [4]). Cost-effectiveness is thereby defined as the annual cost for each unit of pollution abatement (e.g. x Euro / kg N emission reduction). Likewise, Zanou et al. [7] define the cost-effectiveness ratio (CE) as the ratio cost/effectiveness. Thereby, the limiting factor is the fixed environmental objective. However, the objective might be not to exceed a given budget. In that case, the effectiveness-cost ratio (EC), i.e. kg N reduction for each Euro spent, should be used. Note that the "cost-effectiveness" of a plan in such a framework can only be determined in relative terms and not in absolute terms.

To identify the most cost-effective set of measures that need to be implemented in order to meet the water quality objective, a linear programming (LP) framework can be used. Considering a set of i potential measures, each having an annual cost c_i (in Euro/year) the cumulative cost function that needs to be minimised is given by:

$$F(x) = \sum_i c_i x_i \tag{1}$$

The LP-model optimises the values of x_i, being the level of implementation of each measure. Hereby, the following constraints have to be taken into account:

$$\sum_i \alpha_i A_i x_i \geq L \tag{2}$$

$$0 \leq x_i \leq \max_i \tag{3}$$

The constraint in eqn (2) states that the total in-stream load reduction should not be less than L (in kgN/year), whereby L is calculated based on the actual load in a control section and the load that is allowed in view of the quality objectives. The in-stream load reduction is calculated, considering the emission load abatement (A; in kg/year), the level of implementation (x) and the immission coefficient (α) of the measures. The immission coefficient is the ratio between the load that reaches the control section and the load that was emitted at the source of the pollution.

The constraint in eqn (3) signifies that the level of implementation cannot exceed a given maximum.

2.2 Cost-benefit analysis

To maximize welfare for those who have to pay for the pollution abatement measures, profit-maximization is to be used as an objective function in a cost-benefit-analysis. Thereby, profit is realized when the benefits to society are larger than the costs. Yet, no prices exist for environmental benefits. What is e.g. the additional monetary benefit of cleaned rivers, or what is the price of biodiversity? Maas and Jantzen (in van der Woerd et al. [1]) classify the existing methods to estimate benefit functions into two large groups: the 'control cost' method and 'impact pathway' method. In the control cost method, benefits are seen as ‘avoided damage costs’ and equal to the costs needed to prevent or restore damage to the environment. In the impact pathway method, it is checked how much people are willing to pay (WTP) for clean water. In this way, the impact of clean water on welfare, on biodiversity or on public health is monetarized, either by complex economic equilibrium models or by means of questionnaires. A cost-benefit analysis can be used to assess the optimal level of pollution for society, i.e. the most cost-efficient solution. Although the impact pathway method does provide a more extensive economic analysis, the required data is often not available. The control cost method is more relevant. For river basin management, a cost-benefit analysis is preferably used when levels of emission reductions have not been fixed externally. Yet, in case of the WFD, the environmental standards are fixed. A cost-effectiveness analysis is therefore the most ‘cost-effective’ method.

3 Case study: the Grote Nete river basin

3.1 Study area

The ‘Grote Nete’ river basin is located in the Flemish Region of Belgium (fig.1). It is a subbasin of the Nete basin, which is part of the international river basin district of the river Scheldt. The Grote Nete basin has an area of 405 km² and is characterized by sandy soil and alluvial sediments. Having an average altitude of 20 mASL and slopes below 2%, the Nete basin is typically a lowland area. The outlet of the basin is taken at the Hulshout measurement station.

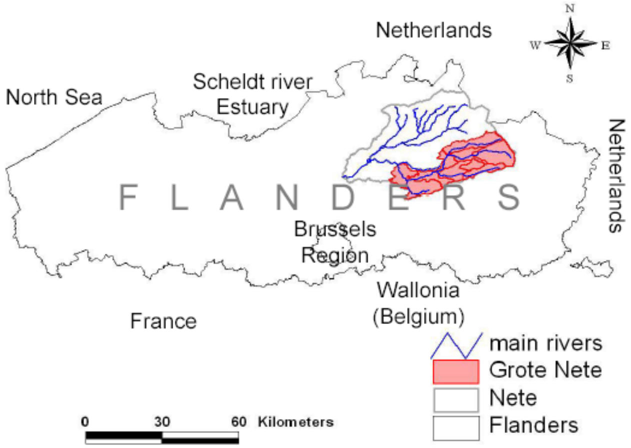

Figure 1: Grote Nete basin in Flanders (Belgium).

The basin has a population density of more than 300 inhabitants per km². Food and chemical industry are the main industrial activities. About 60% of the total area is agricultural land: ca. 70.000 cows, 85.000 pigs and 1.3 million chickens are bred in the area [8]. For the period 2000-2002, the total load discharged in the river by point sources amounts to 1070 kg N_t day^{-1} and 90 kg P_t day^{-1} [9]. At the outlet, an average concentration of 4.2 mgN/l and 0.89 mgP/l is measured.

3.2 Identification of measures

For the sake of the case study, only nitrogen abatement is considered and the abatement measures are limited to: 1) waste water treatment for households not yet connected to a WWTP, 2) subsidized reduction of pigs bred and 3) processing of pig manure prior to application on the field. For each measure, load abatement characteristics are shown in Table 1.

With regard to waste water treatment, about 34000 Inhabitant Equivalents (IE) are not yet connected to a WWTP. It was decided to choose a WWTP size of 10000 IE. Consequently, the maximum level of implementation for this measure corresponds to the construction of 3 new WWTP. The nitrogen content of the influent is assumed to be 10 gN/IE/day. The average nitrogen removal efficiency is 56 % (Aquafin [10]).

Pig reduction represents a farmers' management option. A maximum reduction of 10% of the total pig's livestock is set. The annual emission load of pigs amounts to 10.8 kgN per pig. As only a fraction of this load will reach the river, the immission coefficient for this pollution type is low: a value of 10% was used, as suggested by the Flemish EPA for the Nete basin (VMM [11]).

For manure processing, small-scale units processing 20000 m^3 liquid manure year^{-1} or the manure produced by 1275 pigs are considered. Assuming that a unit consists of a chain of techniques (Feyaerts et al. [12] and VCM and STIM [13]), a nitrogen removal efficiency of 100% is assumed for these units. The maximum potential of these measures is determined by the size of the pig livestock.

Table 1: The selected pollution abatement measures.

measure	N content (kgN/yr)	Unit	A (kg N/yr)	α	max
WWTP	3.65 /IE	1 WWTP = 10000 IE	36500	0.56	3
reduce pigs	10.8 /pig	1 pig	10.8	0.1	8500
manure processing	10.8 /pig	1 unit = 1275 pigs	13770	0.1	67

3.3 Cost of nitrogen abatement measures

Cost estimates (Table 2) are assumed to be average values for the whole basin. Administrative costs of designing and implementing nutrient reduction policies are not considered.

Investment costs (IC) for WWTP were made available by Aquafin, the WWTP operator for the Flemish Region and are in agreement with cost functions by Interwies et al. [3]. Costs related to the construction of sewer networks are not considered. To calculate the operational costs (OC), the rules of thumb from the AFSS database [14] were used: 2% of the investment cost for maintenance, an energy consumption of 0.1 kWh/IE costing 5.63 c€/kWh and 3 days of labour per week. The investment costs are 'annualized', based on a discount rate of 3 % and the lifetime period: 15 years for electronic equipment and 33 years for constructions. The resulting yearly investment cost is called an 'annuity'.

The cost of manure processing is based on Feyaerts et al. [12]. VCM and STIM [13] report an average cost of 25-30 €/ton dry matter, however for less processing capacity. Assuming a dry matter content of 8.5%, this value corresponds to an average cost of 4 €/m³ liquid manure. The economic cost of one pig (less) is set at the level of the government's compensation funds: 117.5 Euro/pig. If a farmer accepts the compensation, he is not allowed to increase his livestock for 10 years, which explains the lifetime of 10 years for this measure.

Table 2: Cost of measures.

measure	IC (€/unit)	OC (€/yr/ unit)	Life time (yr)	annuity (€/yr/unit)	Total cost c (€/year/unit)
WWTP	2.3E+06	5.5E+04	15/33	1.3E+05	1.9E+05
reduce pigs	117.5	0.0	10	13.8	14
manure processing	3.8E+05	4.8E+04	15	3.2E+04	8.0E+04

4 Results

4.1 CE ratio

The CE ratio for the different abatement measures, as defined in §2.1, is shown in table 3. The construction of a WWTP proves to be the most cost-effective measure, while manure processing is the least cost-effective. However, one should be aware that the cost/effectiveness ratios shown in table 3 for diffuse pollution are strongly affected by the immission coefficient, α. Obviously, the latter should thus be set as a result of careful investigation.

Table 3: CE ratios and immission coefficients.

measure	CE ratio (€/kgN abatement)
WWTP	9.2
reduce pigs	12.8
manure processing	58.1

4.2 Most cost-effective combination: results from the LP model

To assess the total cost to achieve a good status in the most cost-effective way, costs and effectiveness of the three measures are entered into a linear programming (LP) model. Based on averages in 2000-2002 for the in-stream concentration for total nitrogen of 4.2 mgN/l, the environmental standard of 2.2 mgN/l and a mean flow of 3.79 m^3/s, a load reduction target at the outlet of 263 tonN/year has to be achieved.

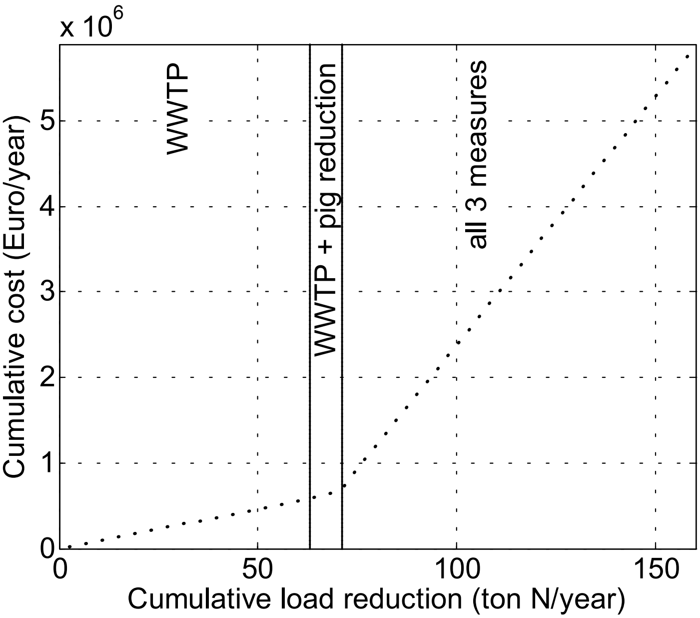

Figure 2: Results from the LP model for nitrogen.

Fig.2 shows the cumulative cost for each load reduction up to the environmental standard for nitrogen. The final load reduction target (263 tonN/year), however, cannot be met. Above a load reduction of 160 tonN/year reduction, i.e. at 62% of the objective, it is technically not feasible to achieve further load reductions. The LP model can no longer find an optimum because either the total load reduction cannot be reached (eqn 2) or because measures are applied above the maximum potential (eqn 3).

The cumulative cost to achieve the maximum possible reduction amounts to 6 million € per year and has to be maintained for 10-15 years. By 2015, the accumulated cost will therefore be more than 70 million €. Furthermore, fig.2 shows which combination of measures is the most cost-effective at each step in load reduction. The add-on of a new measure is marked by a discontinuity in the curve and shown by a vertical line. At first, the most cost-effective measure, having the smallest in-stream CE ratio, will be applied, i.e. WWTP. However, when 24 % of the target is reached, the maximum potential, i.e. 3 WWTP's, are to be constructed. For further load reductions, the second most cost-effective measure, i.e. a reduction of pigs, is added. At maximum, the combination of both measures can reduce the load up to 71 tonN/year (or 27%). Hereafter, manure processing can additionally be applied. As the target could not be met, even after full implementation of all measures, the rate of implementation, x_i is maximal and equal to max_i.

5 Discussion and conclusions

With high environmental concerns and limited financial resources, good water quality has to be reached in the most cost-effective way. For the Grote Nete river basin (Belgium), the following measures are considered for the abatement of nitrogen emissions: waste water treatment, a reduction of pigs and manure processing. To identify the most cost-effective set of measures, that will achieve good water quality, a linear programming (LP) framework is applied. The final load reduction target could not be achieved even when the three proposed measures become fully implemented. The maximum achievable load reduction is 62% of the target. More pollution abatement measures should therefore be considered.

The results show that that the nutrient abatement costs are typically convex, which implies that abatement costs rise at an increasing rate with increasing emission reduction targets. Similar results were e.g. obtained by van der Veeren [4] and Johansson et al. [16]. To achieve the final 38 % of load reduction, the abatement costs will therefore rise rapidly. No doubt, the consideration of other measures than the ones considered in this paper may achieve the same result at lower cost. As also stated by Johansson and Randall [15] it is however unlikely that the curvature of the cost curve will be affected by the addition of additional measures.

The lumped approach used in this paper, in which the spatial distribution e.g. of the newly constructed WWTP's is not required, may be considered as an advantage. However, the method requires the determination of immission coefficients, based on expert judgements. As the latter values appear to be most sensitive, more research on this issue is required. Possibly, the setting of the immission coefficients could be based on modelling.

Although the case study that was considered in this paper is a simple one, it illustrates the importance of designing policies that account for the cost implications of different strategies. When considering that the number of possible implementation schemes increases as the size of the watershed and the number of variables increase, the use of an optimization algorithm for river basin management is essential.

Given that water pollution affects almost everybody and given the high costs to restore a good water status, the question who has to pay for pollution reduction efforts and who will profit from the clean resources is becoming more and more important. If the distribution of the costs and the benefits of environmental policies among the various actors is considered to be fair, then the implementation of these policies may be easier than in cases where this distribution is considered to be unequal and unfair (van der Veeren [4]). For example, economically efficient solutions may not always be regarded as fair, whereas a uniform emission reduction is more expensive (Schleich et al. [17]). Therefore, for the actual distribution of efforts and benefits, value judgements and ethical considerations on equity should be incorporated in the methodology (van der Veeren and Lorenz [18]).

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